Acoustic Resonance Classification of Swimbladder-Bearing Fish at Multiple Scales

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LONG-TERM GOALS

Accurately describe the spatial and temporal distributions of fish and quantify the mid-frequency clutter characteristics of fish.

OBJECTIVES

To conduct a new class of quantitative studies of acoustic scattering by swimbladder-bearing fish utilizing new broadband-acoustic technology that is optimized for use in the resonance scattering region of fish. The studies, which include use of a long-range horizontal-looking system and a short-range downward-looking system, exploit the resonance scattering of the fish to significantly reduce ambiguities in the interpretation of the data.

APPROACH

Building on the success of three previous major experiments, which includes the NRL pilot measurements in 2008, we have made a fully-integrated set of measurements through two two-ship experiments (Sept. 2010 and Sept. 2011) involving a NOAA fisheries vessel and a UNOLS vessel. We

1

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are exploiting the broadband capabilities of each of the mid-frequency acoustic systems (WHOI-Edgetech and NRL systems), along with their complementary deployment geometries (short-range downward-looking vs. long-range horizontal-looking, respectively) for both resonance classification of swimbladder-bearing fish and characterization of their patchiness at different spatial and temporal scales. Province-wide variability of the fish distribution, resonance signature, and clutter features are studied with the long-range system while the strong depth dependence of the resonance, multiple resonances associated with mixed assemblages, and short-range patch structure (in the vertical plane) are studied with the short-range system. Complementing these mid-frequency measurements is the use of nets to sample the fish and traditional high frequency acoustics for intercomparison with standard techniques (NOAA/NMFS).

The end results of the measurements are first-of-a-kind maps of distributions of swimbladder-bearing fish in two planes (vertical and horizontal) as derived from two broadband mid-frequency sonars at multiple scales. *What makes these results unique and powerful is that, not only are the data collected at high spatial resolution in these two orthogonal planes, but the data are also broadband and contain resonance information eliminating significant ambiguities in interpretation.* In addition, key parameters relevant to Navy signal processing systems of the echo statistics of the long-range sonar due to the patchiness are determined, allowing the development of physics-based bioclutter models and clutter-reduction methods.

Tim Stanton (WHOI) oversees the entire program and is involved in every aspect, with an emphasis on the WHOI short-range downward-looking system. Cindy Sellers (WHOI) prepares for and participates in the cruises, as well as processes and analyzes data. Ben Jones (NPS) participates in data analysis and modeling. Mike Jech (NOAA/NMFS) conducts the biological sampling, performs high frequency acoustic surveys, and is involved in the design and execution of the cruises. Roger Gauss (NRL) leads the NRL team (including Richard Menis, Ed Kunz, and Joe Fialkowski) involving use of their prototype mid-frequency broadband system for long-range detection and classification of fish.

WORK COMPLETED

This year involved processing and analyzing data from the September 2011 cruise as well as submitting and publishing papers based on this and previous years' work. In addition, two students on this project (Ben Jones and Saurav Bhatia) received graduate degrees this year (Ph.D. and M.S., respectively).

1. Research papers
Much of the previous year's work came to fruition this year as one paper was published (refereed), three new ones were submitted (to refereed journals), and two dissertations based on this work were completed. One of the newly submitted papers was an invited review article on the subject which included some of our cruise results.

Published paper
This paper describes use of resonance classification to study mixed assemblages of fish. Here, major size classes of fish are spectrally resolved with our downward-looking broadband acoustic system and quantified in the case where traditional narrowband echosounders are inadequate (Stanton et al., 2012).

Submitted papers

a. Echo statistics from mixed assemblages (narrowband signals). This theoretical study formulates an exact expression for echo statistics from mixed assemblages of scatterers of varying sizes and numerical densities. This was inspired by the above resonance scattering study of mixed assemblages. The results are superior to those from the commonly used "mixture probability density function (PDF)" (Lee and Stanton, submitted).

b. Echo statistics from randomly oriented elongated scatterers. This theoretical study formulates expressions for echo statistics from randomly oriented prolate spheroids under various conditions—varying aspect ratio, with and without surface roughness, and with and without beampattern effects. This quantifies the degree to which the signals are non-Rayleigh for the various conditions and connects the physics of the scattering to parameters of the statistics. (Bhatia et al., submitted).

c. Review of 30 years of advances in active bioacoustics. This article was invited as a means to "kick off" the first issue of a new journal, Methods in Oceanography. (Stanton, in press).

Dissertations

a. *"Echo statistics of aggregations of scatterers in a random waveguide: Application to biologic sonar clutter"* (Ben Jones, Ph.D., 2012). This was a two-pronged study that first modeled echo statistics due to various combinations of aggregations of scatterers (inspired by the fish application) for a long-range mid-frequency sonar and then applied the results to our Sept. 2011 cruise data. The cruise analysis not only analyzed the echo statistics, but also tied the spectral properties of the broadband echoes to the sizes and species of fish sampled in the area. The dissertation serves as the basis for two future journal articles. One of the articles is currently being prepared for submission.

b. *"Non-Rayleigh scattering by a randomly oriented elongated scatterer" (Saurav Bhatia, M.S., 2012).* This dissertation is based on the submitted paper described above. It contains a number of simulations beyond what is in the paper as well as software.

2. Key tasks completed

Modeling

Significant progress was made in modeling echo statistics from various types of scatterers and assemblages of scatterers, as described in the papers and dissertations listed above. The modeling was inspired, in part, by our analyses of cruise data. These studies connect the physics of the scattering to parameters of the statistics which, in turn, allow meaningful biological parameters to be inferred from the echo statistics.

Work was completed on narrowband direct-path echoes associated with single scatterers (prolate spheroids of varying aspect ratios) and assemblages of scatterers (of varying sizes and numerical densities). Work was also completed on both narrowband and broadband long-range echoes (with ocean waveguide effects) for various assemblages of scatterers. Finally, in a new effort started this year, statistics of broadband direct-path echoes from assemblages of scatterers have been studied. Both development of theory and comparison with our ocean data were conducted in this latter case and a manuscript has been drafted.

Cruise data

The broadband sonar data and net samples from the 2011 cruise were integrated, resulting in definitive descriptions of the fish aggregations as sampled by the long-range sonar (Figs. 1-5). After all data were processed, the analysis involved several major steps—classifying the echoes as being due to fish, modeling the spectral (resonance) content of the echoes in terms of the different species and sizes of fish present, and characterizing the echo statistics.

We observed that in one particular area (Franklin Swell), the fish formed dense, compact aggregations. The aggregations were generally sparsely distributed in the region. The echoes from the aggregations were strong and well above the levels from other sources of reverberation (Fig. 4). The echo spectra contained one or more resonances, consistent with the presence of swimbladder-bearing fish (Fig. 3). The modeled resonances were consistent with the fish sampled in the area (Fig. 2). Finally, the echo statistics are strongly non-Rayleigh, showing that the fish are a potentially significant source of clutter in Navy systems (Fig. 5).

RESULTS

We have demonstrated that at long ranges and mid frequencies (1-9 kHz), echoes from aggregations of fish can dominate other sources of reverberation in this coastal region, and moreover that the spatial characteristics of fish and their echo statistics are specific to geographical region (Jeffreys Ledge: dispersed; Franklin Swell: compact/sparse; and Georges Bank: shoals/large aggregations). We have further demonstrated that we can classify the long-range data in terms of the resonances associated with the presence of the various sizes and species of swimbladder-bearing fish. Our statistical analyses of echoes, both theoretical and experimental, have quantified the connections between biologically meaningful properties and parameters, associated scattering physics, and parameters of the statistical distributions. The degree to which the echoes are non-Rayleigh is a complex function of sonar system parameters (e.g., the source and receiver beampatterns), scatterer type (such as size and shape) and scattering geometry (including waveguide effects and spatial distribution of scatterers).

IMPACT/APPLICATIONS

Our complementary sets of high-resolution short- and long-range broadband (1-9 kHz) data are a first of a kind and are revealing important information on the behavior of fish. The advanced broadband approach provides new insight into biological processes over conventional approaches: a) both broadband systems are well suited for determining fish size through resonance classification (conventional narrowband acoustic systems cannot determine size); and b) the long-range sonar is well suited for rapidly and synoptically sampling sparsely-distributed dense compact aggregations of fish (conventional systems grossly under-sample sparse distributions). This approach of using broadband sound in two planes (vertical and horizontal) sets a new high standard by which acoustic measurements should be made in order to characterize distinct classes of fish.

The scientific benefits include new insights into: a) predator-prey relationships (from resonance classification of multi-size fish assemblages); and b) region-specific behavior of fish (from spatial mapping).

The Navy benefits include new information on quantifying both the regional variability of bioclutter and the clutter characteristics that, in turn, can be used to enhance ASW sonar performance (see "Transitions").

TRANSITIONS

We are currently scheduled for our second transition of our work: the Common Acoustic Simulation Environment (CASE) trainer for air-deployed ASW sonars. This builds on last year's transition to the Advanced Capability Build 13 (ACB 13) of the Surface Ship ASW Synthetic Trainer (SAST) (PEO IWS 5A). Both of these transitions are based on results from our work on our pilot cruise that preceded this project and via a sequence of the ONR Undersea Signal Processing D&I program (Keith Davidson) and the High Fidelity Active Sonar Training (HiFAST) FNC program (Mike Vaccaro) and in collaboration with Dr. Brian La Cour of ARL:UT and LCDR Ben Jones of NPS. Below is a summary of the sequence for both transitions:

1) The statistical properties of mid-frequency echoes from fish were measured in our pilot cruise in 2005. In that cruise, the patchiness of the fish was observed at high resolution through towing our system (funded by ONR DURIP) deep and just over the patches of fish. The data spanned several important geometries—sonar beam within a patch, sonar beam sweeping across one patch edge, and sonar beam sweeping across multiple patches.

2) The data described in #1 above served as the basis for developed analytical descriptions of the sonar echo statistics in the ONR Undersea Signal Processing program. Models were developed appropriate for each scattering geometry. Furthermore, a general echo statistics model was developed, inspired by this first analysis.

3) In the HiFAST program, we modeled the clutter due to patches of fish. Part of the analysis involved use of the scattering models that we applied in analyzing the data in this current (ONR Biology) program. Hence the models were grounded with scientific data (which included net samples provided by NOAA/NMFS). Furthermore, via simplifying assumptions in the modeling, computation time was reduced (essential for synthetic trainers). The fidelity of these simplified models was tested, in part, through use of the new statistics models that we developed in #2 above.

RELATED PROJECTS

1. Stanton has been funded through the Undersea Signal Processing Division of ONR to study the statistics of the fish echoes (sequence of D&I grants N00014-07-1-0232 and N00014-09-0428). The data from this (Biology) program have been used as a basis for studying echo statistics of mid-frequency echoes due to the presence as fish (Stanton and Chu, 2010) as well as to inspire development of new advanced theoretical formulations for echo statistics. **2.** Stanton is currently funded through the Undersea Signal Processing Division of ONR to study statistics of echoes from elongated objects (D&I grant N00014-11-1-0116). The results in that project are general and apply to fish in this (Biology) program. **3.** Under the HiFAST FNC program of ONR (grant N00014-11-1-0241; Mike Vaccaro), Stanton has collaborated with Drs. Brian LaCour of ARL:UT and LCDR Ben Jones of NPS to *transition* the new knowledge that originated in this project to the ACB13 SAST system. Another transition is scheduled for the CASE (see above in "Transitions"). Other Navy systems are targeted for future transitions. **4.** Commencing in FY10, Stanton and Gauss have participated on a PEO C4I & Space (PMW 120; Marcus Speckhahn) panel to help develop a phenomenological approach that can nowcast/forecast spatial distributions of biologics for mid-frequency ASW applications based on oceanographic, biologic, and acoustic data and models. **5.** Gauss is also on the ONR 322OA (Robert

Headrick) Applied Reverberation Modeling Board (ARM-B) whose charter is to understand the limitations/major challenges presented by today's and tomorrow's active sonars relative to reverberation and clutter predictive capabilities, and recommend solutions (the way ahead). Its initial focus is on mid-frequency active monostatic sonars. Both # 4 and 5 allow Stanton and Gauss to identify and act on technology insertion points. **6.** Gauss is currently funded by PMW-120 to use archival fish information (the literature and high-fidelity acoustic data) to: a) establish the viability and procedures for systematically estimating volume scattering strength (VSS) (via NRL's Fish Scattering Strength (FSS) algorithm); and b) transition these statistical estimates to the VSS Database in CNMOC's Oceanographic and Atmospheric Master Library (OAML), the repository of Navy-standard algorithms, databases, and models. The planned Stanton enhancements to his scattering formulations could serve as a basis of FSS upgrades. **7.** Gauss has been developing moment-based clutter-rejection techniques for improving automated active Navy classifiers that will be under evaluation for transition to the ACB AN/SQQ-89 A(V) 15 system (ACB-17) in FY12-14 under the ONR Active Sonar Automation Enabling Capability Project (Keith Davidson). **8.** Gauss is also collaborating with NUWC (Wendy Petersen—2010 cruise participant—and Jenna McKown) in determining the potential impact of bioclutter on Navy automated trackers, and the ability of moment-based methods to characterize and control false tracks due to bioblutter.

PUBLICATIONS

Refereed journals
Stanton, T.K., C. Sellers, and J.M. Jech (2012) "Resonance classification of mixed assemblages of fish with swimbladders using a broadband echosounder at 1-6 kHz," *Can. J. Fish Aq. Sci.* **69**: 854-868. [published, refereed]

Stanton, T.K. (in press), "30 years of advances in active bioacoustics: *A personal perspective,"* Methods in Oceanography, doi:10.1016/j.mio.2012.07.002. (Invited review article). [in press, refereed]

Lee, W.-J. and T.K. Stanton (submitted), "Statistics of echoes from mixed assemblages of scatterers with different scattering amplitudes and numerical densities," submitted to IEEE J. Ocean. Eng. [submitted, refereed]

Bhatia, S., T.K. Stanton, and K. Baik (submitted), "Non-Rayleigh scattering by a randomly oriented elongated scatterer randomly located in a beam," submitted to IEEE J. Ocean. Eng. [submitted, refereed]

Dissertations
Jones, B. A. (2012), "Echo statistics of aggregations of scatterers in a random waveguide: Application to biologic sonar clutter", Ph.D. dissertation, Naval Postgraduate School. [published]

Bhatia, S. (2012). "Non-Rayleigh scattering by a randomly oriented elongated scatterer", M.S. thesis, MIT/WHOI. [published]
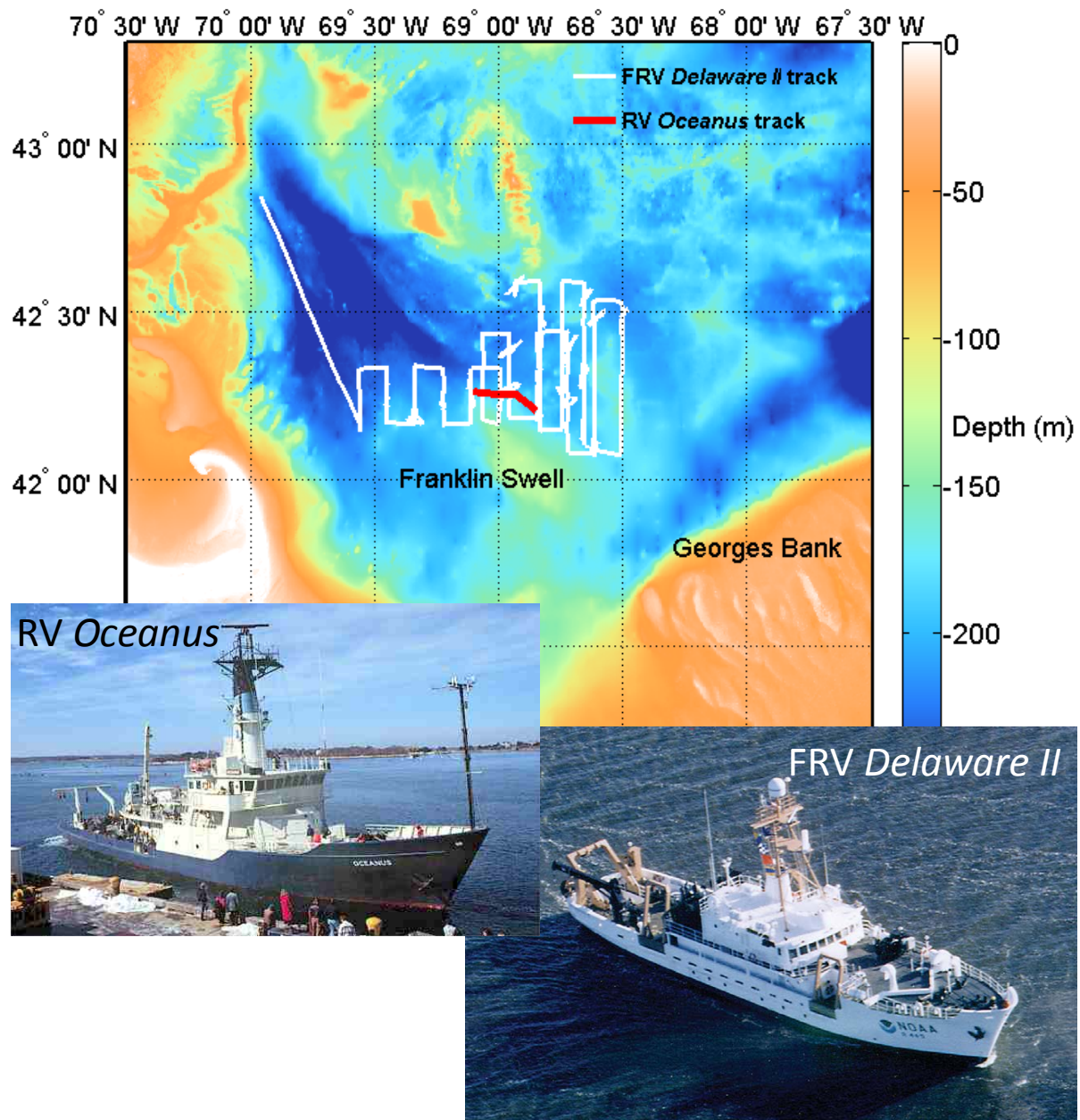
Figure 1. Two-ship experiment in Gulf of Maine in September 2011. The ship tracks shown in the top image correspond to the Franklin Swell component of the experiment (adapted from Jones, 2012).
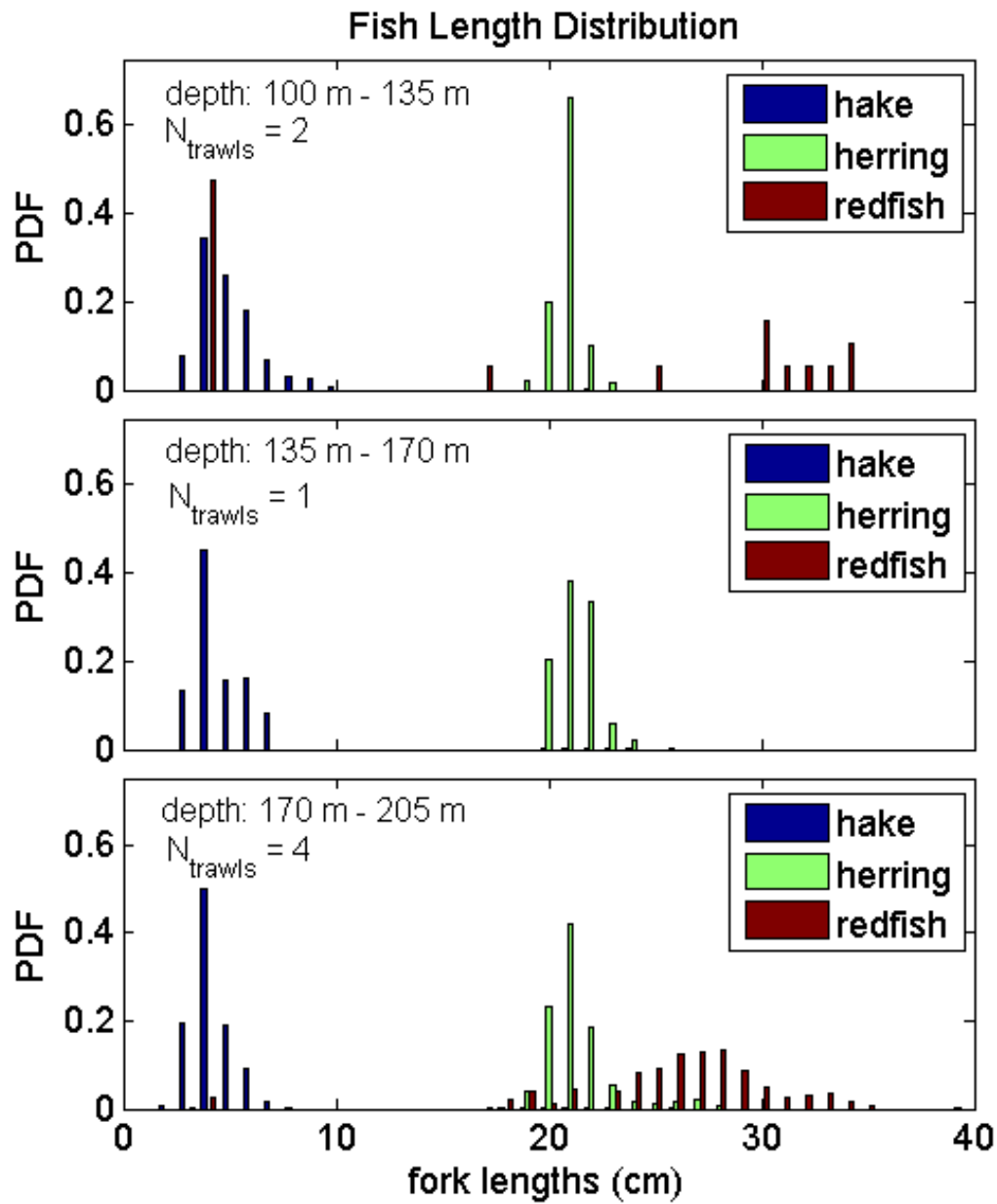
Figure 2.   Samples of fish collected by NOAA Fisheries from the Franklin Swell area (adapted from Jones, 2012).
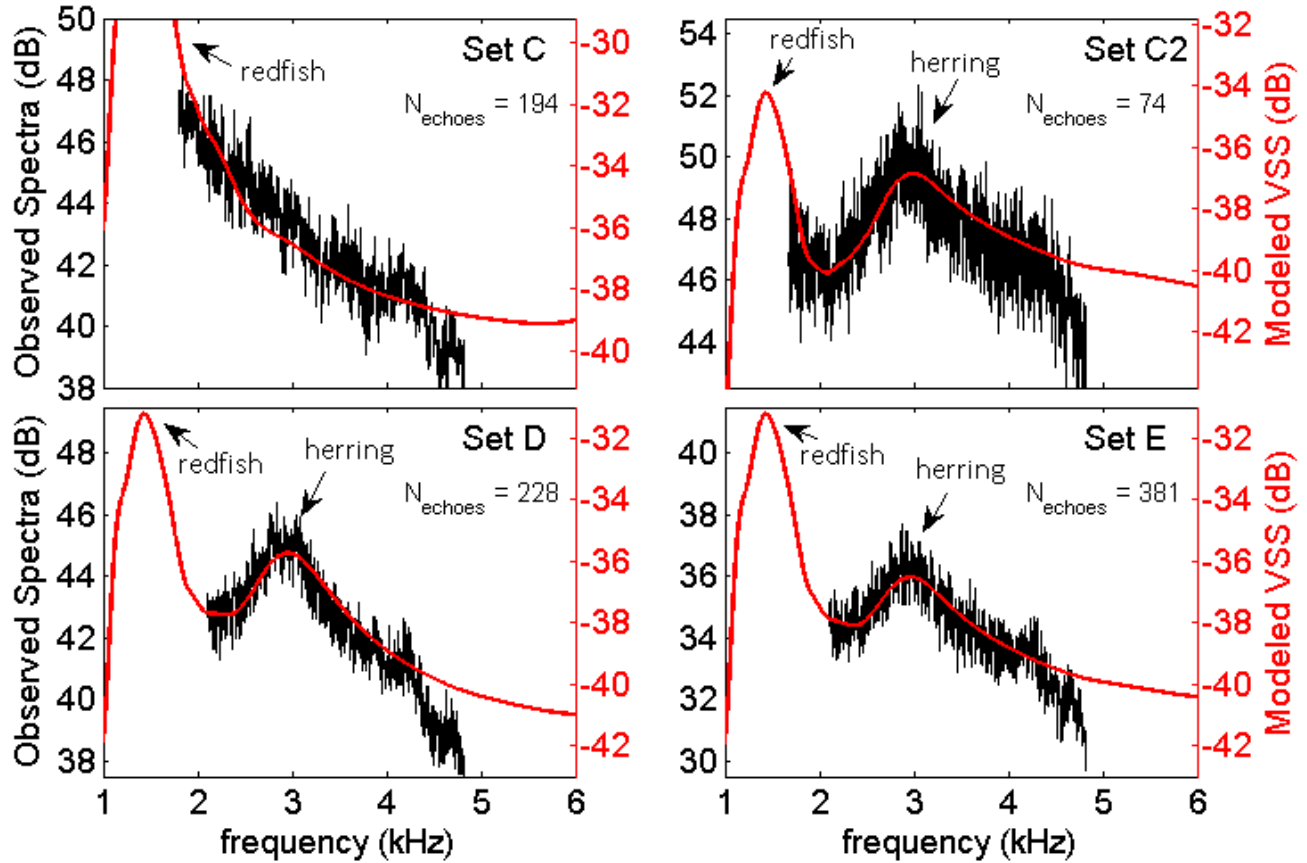
Figure 3. Spectra of observed and modeled mid-frequency echoes from two species of fish from the Franklin Swell area (adapted from Jones, 2012).

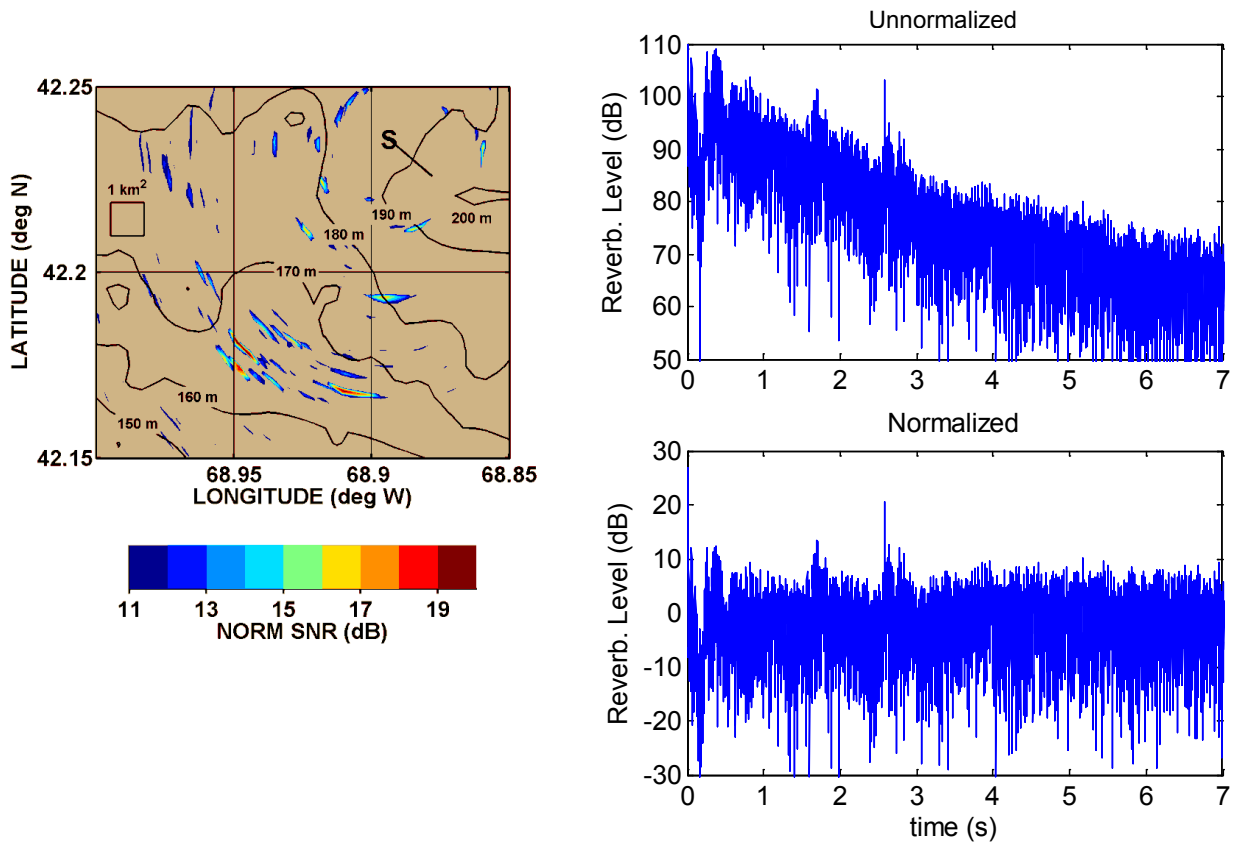# Long-Range Acoustic Measurements of Fish Schools

Figure 4. Matched filter output of long-range sonar echoes from fish in the Franklin Swell area: (left) georeferenced normalized echoes superimposed with bathymetric contours; and (right) normalized (bottom) and unnormalized (top) echoes for one look direction (beam 27). (Adapted from Jones, 2012.)
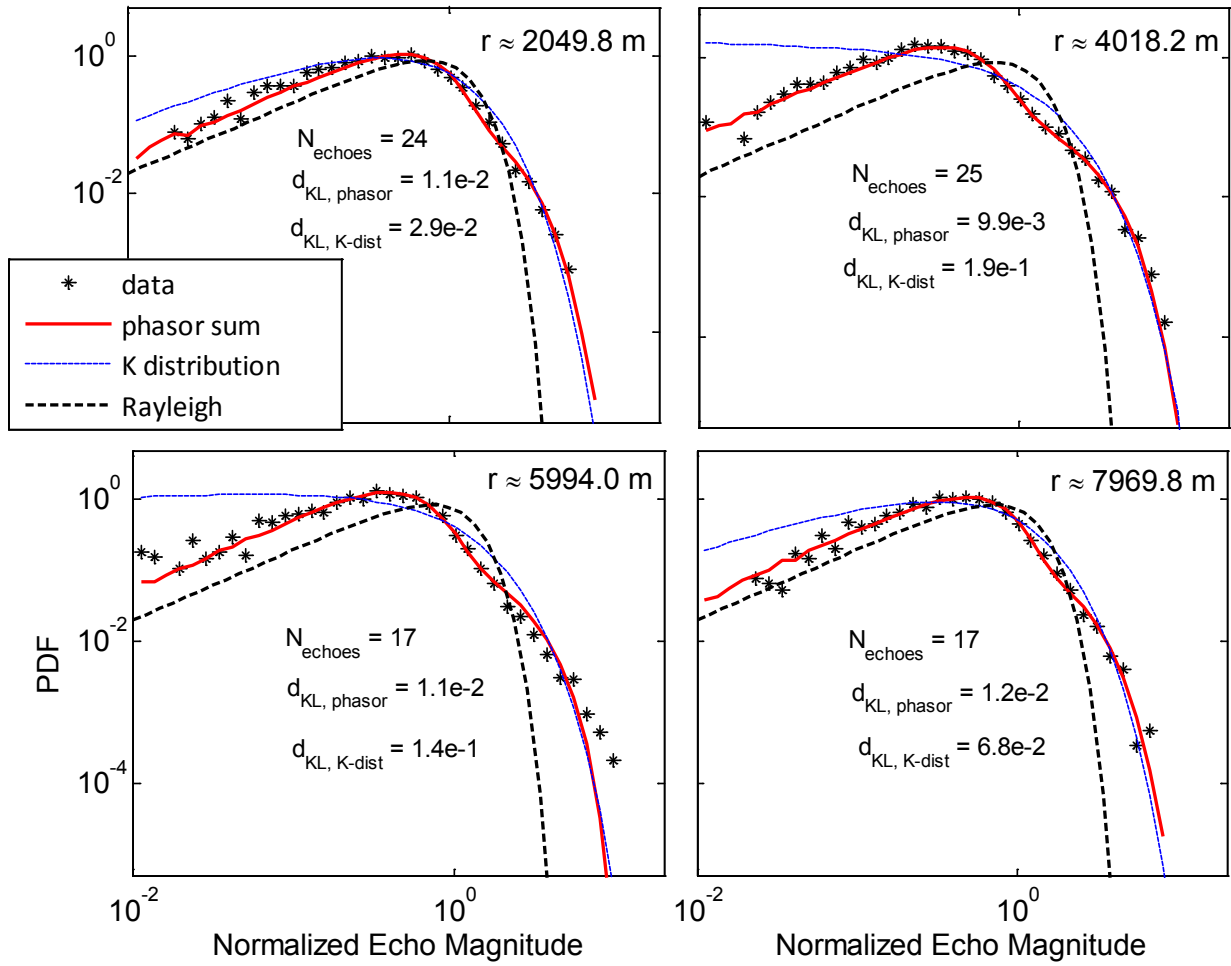
Observed Echo Statistics

Figure 5. Statistics of long-range mid-frequency echoes from fish at various ranges in the Franklin Swell area. The degree to which the echoes are non-Rayleigh is illustrated, as well as comparison with two models. (Adapted from Jones, 2012.)